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# Fabricating third-order nonlinear optical susceptibility of impurity doped quantum dots in the presence of Gaussian white noise

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ABSTRACT

We perform a meticulous analysis of profiles of third-order nonlinear optical susceptibility (TONOS) of impurity doped quantum dots (QDs) in the presence and absence of noise. We have invoked Gaussian white noise in the present study and noise has been introduced to the system additively and multiplicatively. The QD is doped with a Gaussian impurity. A magnetic field applied perpendicularly serves as a confinement source and the doped system has been exposed to a static external electric field. The TONOS profiles have been monitored against a continuous variation of incident photon energy when several important parameters such as electric field strength, magnetic field strength, confinement energy, dopant location, *Al* concentration, dopant potential, relaxation time, anisotropy, and noise strength assume different values. Moreover, the influence of mode of introduction of noise (additive/multiplicative) on the TONOS profiles has also been addressed. The said profiles are found to be consisting of interesting observations such as *shift of TONOS peak position* and *maximization/minimization of TONOS peak intensity*. The presence of noise alters the features of TONOS profiles and sometimes enhances the TONOS peak intensity from that of noise-free state. Furthermore, the mode of application of noise also often tailors the TONOS profiles in diverse fashions. The observations accentuate the possibility of tuning the TONOS of doped QD systems in the presence of noise.



## 1. Introduction

Distinct changes in the electronic and optical properties of low-dimensional semiconductor devices can be obtained by the presence of impurity. This important aspect has made impurity doping in mesoscopic systems a ubiquitous research topic. Investigations on impurity states have been further accelerated because of their immense importance in physics and technological applications of quantum dots (QDs). Impurity causes significant change in the energy distribution of doped QD and makes the way to achieve controlled optical transitions. Controlled optical transition is of utmost importance for manufacturing optoelectronic devices with tunable emission or transmission properties and ultranarrow spectral linewidths. Furthermore, the intimacy between the optical transition energy and the confinement strength (or the quantum size) makes fine-tuning of the resonance frequency very much obtainable. Apart from this, in the study of the optical properties of low-dimensional semiconductor systems, the analysis of impurity states merits importance because the confinement of carrier in such systems leads to enhancement of oscillator strength (OS) of electron-impurity excitation [1]. As a consequence, optical properties of doped QDs and other neighboring low-dimensional systems have envisioned tremendous research activities [2–29].

Nonlinear optical (NLO) properties of semiconductor QDs and quantum wells (QWLs) have gained sincere attention owing to their unquestionable ability of being utilized as a probe for the electronic structure of mesoscopic media. Moreover, NLO properties of low-dimensional materials have indicated enough promises for application in electronic and optoelectronic devices (e.g. far-infrared laser amplifiers, photodetectors, electro-optical modulators, and all optical switches) in the infra-red region of the electromagnetic spectrum [30]. The NLO properties connected with intersubband transitions in low-dimensional systems shed light on important fundamental physics. This is because of pronounced enhancement of the nonlinear effects in these low-dimensional quantum systems over those in the bulk materials exploiting quantum confinement effect [31]. The said confinement leads to small energy interval between the subband levels, large value of electric dipole matrix elements and greater opportunity of

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attaining the resonance conditions. In what follows, these nonlinear properties have revealed many pathways for fabricating a lot of optoelectronic devices such as far-IR laser amplifiers, photodetectors, and high-speed electro-optical modulators [32–34].

It is due to the existence of $\delta$-like density of states, large optical nonlinearities are also quite obvious in semiconductor QDs. The transitions between the confined levels in the conduction or in the valence bands have been monitored using different techniques and the optical nonlinearities associated with these intraband transitions are anticipated to be large for the reason that the intraband dipole lengths stretch over the QD size and are about a fraction of nanometers [35]. Achievement of large optical nonlinearities accompanying the intersubband transitions of QD appears highly relevant in the area of integrated optics and optical communications [36,37].

Among various NLO properties the *third-order* members deserve special emphasis in several quantum systems having inversion symmetry. In this case, while the second-order susceptibility disappears because of the inversion symmetry, the third-order one survives and often exhibits huge enhancement compared with the bulk material [38,39]. Therefore, for low-dimensional quantum systems devoid of inversion symmetry, generally only the second-order NLO properties are put under scanner, while the third-order NLO properties suffer from lack of appropriate attention [40]. The augmented magnitude of the third-order nonlinearities in the low-dimensional systems compared with the bulk materials arises out of the quantum confinement effects producing large oscillator strength of intersubband transitions and from the band structure engineering, often supporting the triple resonance requirements [41,42]. As a matter of fact nonlinear optical materials with large *third-order nonlinear optical susceptibilities* (*TONOS*) $\chi^{(3)}$ have emerged as indispensable candidates to manufacture all-optical switching, modulating and computing devices [31] and also in some photonic devices [43] because of which they have drawn much attention. TONOS of these materials not only can be vastly increased but also can be altered by various manufacturing processes. As a consequence, we are able to find an abundance of important works on $\chi^{(3)}$ by Xie [1,50,55], Liu et al. [31], Wang and Xiong [35], Bahari and Moghadam [43], Takagahara and Hanamura [44], Takagahara [45], Zhang et al. [46,47], Zeng et al. [48], Radovanović et al. [49], Feng et al. [51], Xie et al. [52], Cristea et al. [53], and Liao and Xie [54], to mention a few.

In some of our recent works we have made detailed discussions on how *noise* influences the optical properties of QD devices [56–58]. In these works the role of *Gaussian white noise* in the *polarizabilities* of doped QDs has been critically investigated. In the current paper we advocate the influence of *Gaussian white noise* on the *third-order nonlinear optical susceptibility* (*TONOS*) of doped QD. The system under study is a 2-d QD (*GaAs*) consisting of single carrier electron under parabolic confinement in the $x$–$y$ plane. The QD is doped with an impurity represented by a Gaussian potential in the presence of a perpendicular magnetic field which appears as an additional confinement. In view of computing TONOS an external static electric field has been applied to the system. Gaussian white noise has been introduced to the doped QD via two different pathways i.e. additive and multiplicative [56–58]. The profiles of TONOS are pursued with variations of confinement frequency ($\omega_0$), electric field strength ($F$), dopant location ($r_0$), magnetic field strength ($B$), impurity potential ($V_0$), relaxation time ($\tau$), anisotropy, noise strength ($\zeta$), and the mode of application of noise (additive/multiplicative). In addition, $Al_xGa_{1-x}As$ QD has also been examined in order to find the contribution of $Al$ concentration ($x$) on the profiles of TONOS in the presence and absence of noise.

## 2. Method

The impurity doped QD Hamiltonian, exposed to external static electric field ($F$) applied along $x$ and $y$-directions and spatially $\delta$-correlated Gaussian white noise (additive/multiplicative) can be written as

$$H_0 = H_0' + V_{imp} + |e|F(x+y) + V_{noise}. \tag{1}$$

Under effective mass approximation, $H_0'$ represents the impurity-free 2-d quantum dot with single carrier electron shackled by lateral parabolic confinement in the $x$–$y$ plane and in the presence of a perpendicular magnetic field. $V(x, y) = \frac{1}{2}m^*\omega_0^2(x^2+y^2)$ is the confinement potential with $\omega_0$ being the harmonic confinement frequency. $H_0'$ is therefore given by

$$H_0' = \frac{1}{2m^*}\left[-i\hbar\nabla + \frac{e}{c}A\right]^2 + \frac{1}{2}m^*\omega_0^2(x^2+y^2). \tag{2}$$

$m^*$ stands for the effective mass of the electron inside the QD material. Using Landau gauge [$A = (By, 0, 0)$, where $A$ is the vector potential and $B$ is the magnetic field strength], $H_0'$ becomes

$$H_0' = -\frac{\hbar^2}{2m^*}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right) + \frac{1}{2}m^*\omega_0^2x^2 + \frac{1}{2}m^*(\omega_0^2+\omega_c^2)y^2 - i\hbar\omega_c y\frac{\partial}{\partial x}, \tag{3}$$

$\omega_c = eB/m^*$ being the cyclotron frequency. $\Omega^2 = \omega_0^2 + \omega_c^2$ can be viewed as the effective confinement frequency in the $y$-direction.

$V_{imp}$ is the impurity (dopant) potential formulated by a Gaussian function [56–58] viz. $V_{imp} = V_0\, e^{-\gamma\left[(x-x_0)^2+(y-y_0)^2\right]}$. Positive values for $\gamma$ and $V_0$ represent repulsive impurity. $(x_0, y_0)$ is the site of dopant inclusion, $V_0$ is the strength of the dopant potential, and $\gamma^{-1}$ represents the spatial region over which the influence of impurity potential is dispersed. $\gamma$ here acts equivalent to that of static dielectric constant ($\varepsilon$) of the medium and can be written as $\gamma = k\varepsilon$, where $k$ is a constant. In this context it seems pertinent to mention that Khordad and his associates used a new type of confinement potential for spherical QD's called *Modified Gaussian Potential*, *MGP* [59,60].

The term $V_{noise}$ represents the noise contribution to the Hamiltonian $H_0$. It comprises of a spatially $\delta$-correlated Gaussian white noise [$f(x, y)$] which follows a Gaussian distribution (generated by the Box–Muller algorithm) having strength $\zeta$ and is described by the set of conditions [56–58]:

$$\langle f(x, y)\rangle = 0, \tag{4}$$

the zero average condition, and

$$\langle f(x, y)f(x', y')\rangle = 2\zeta\delta\big((x, y) - (x', y')\big), \tag{5}$$

the spatial $\delta$-correlation condition. The Gaussian white noise can be applied to the system by means of two different modes (pathways) i.e. additive and multiplicative [56–58]. These two different modes actually modulate the extent of system-noise interaction. In the case of additive white noise $V_{noise}$ becomes

$$V_{noise} = \lambda_1 f(x, y). \tag{6}$$

And with multiplicative noise we can write

$$V_{noise} = \lambda_2 f(x, y)(x + y). \tag{7}$$

The parameters $\lambda_1$ and $\lambda_2$ take care of all the neighboring influences in the case of additive and multiplicative noise, respectively. At a first sight, it seems that the presence of multiplicative noise would cause greater deflection of the optical properties from that of noise-free condition than due to the presence of additive noise. This is because of greater mingling of noise with system